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Emerging NDE Technologies and Challenges at the Beginning of the 3rd Millennium – Part II

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ABSTRACT

As we begin the third millennium it can be useful to bookmark the state-of-the-art of the NDE field and examine the challenges that are facing the field. As could be seen from Part I of this two-part paper, the field of NDE is now relatively mature and, even though accurate characterization of hidden flaws may still pose a challenge, the last century has been marked with the most incredible progress. Improvements have touched every aspect of the NDE field leading to smaller, lighter and smarter instruments. The requirements for NDE are continuing to be driven by the need for lower cost methods and instruments with greater reliability, sensitivity, user friendliness and high operational speed. In addition to these needs, the technology is sought for applicability to increasingly complex materials and structures. The NDE field is increasingly expanding to new frontiers as a result of improved capabilities and the shift in demand from the traditional areas of aerospace and nuclear industries, partially as a result of the reduction in government funding of related research and development. Moreover, structures are being designed to require less periodic inspection using no fundamentally new material, and there is a lower need for new NDE methods to address such problems as aging aircraft. In this paper, the author made an attempt to summarize the emerging NDE capabilities as well as the challenges. As in Part I, the emphasis is on aerospace related technologies. However, the information is relevant to a wide range of other applications.

INTRODUCTION

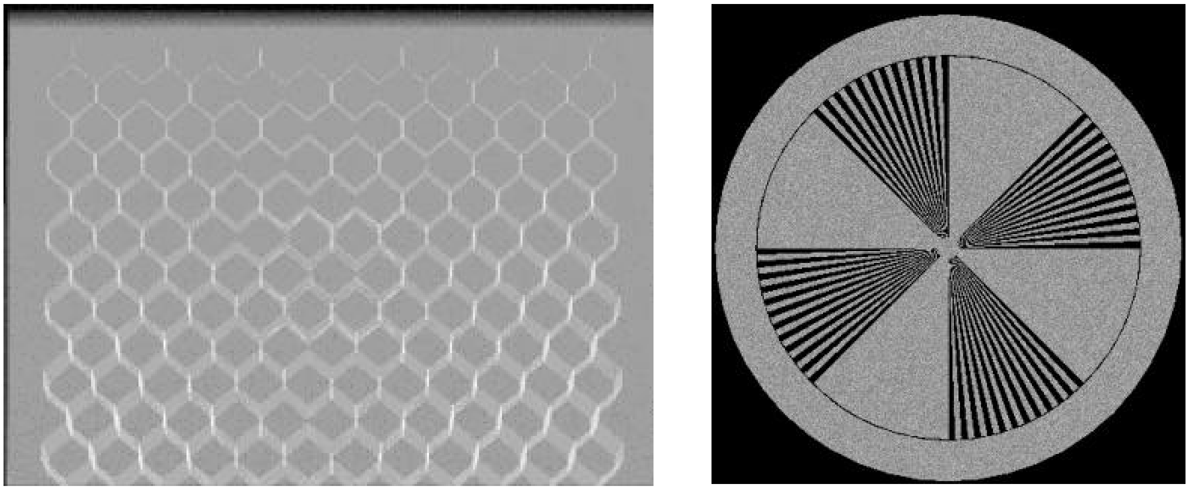
A series of advancements in computers, electronics, material science and other interdisciplinary fields made major impact on all or many of the NDE methods. Accepting the reality that no single method can provide all the necessary NDE information, efforts are being made to integrate several methods. The complimenting capabilities offer greater detectability and the overlapping ones enhance the reliability. Data fusion techniques [Gros, 1996] are being developed to allow effective data-acquisition and processing as well as provide sound interpretation of test parameters in relation to the material integrity. Instruments are now commercially available that used a common platform for ultrasonic and eddy current testing with interchangeable transducers and modules. Also, software packages are available to process data obtained from various NDE methods where, once data is acquired and an image is produced, the results can be analyzed and manipulated using the same software features. The increased processing speed and improvement in hardware is allowing real-time imaging of all the wave-base NDE methods including radiography, ultrasonics, shearography, etc. Using analytical tools, finite element analysis as well as computer hardware and software, test procedures can be developed graphically by interactive process simulation. Moreover, progress in microelectronics led to the development of pocket size instruments. The following discussion covers technologies that affected the field of NDE in general.

Information Highway

In the relatively short time since Internet became the world-wide-web as we know it, this information highway significantly contributed to the advancement of many fields including NDE [Bar-Cohen, et al, 1996]. Internet is now the information communication tool of choice for multimedia (data, files, text, programs, drawings, pictures, video and sound) at speeds, efficiency and content that cannot be matched by any other known method. NDE experts around the world rapidly recognized its power as a form of information exchange and archival. The technology is simplifying and helping to expedite the development of international standards and process specifications, as well as enabling the centralization and easing access to information achieves and databases. Formed in 1995, the global NDE Newsgroup [nde@coqui.ccf.swri.edu], which is maintained on a server at South West Research Institute, is widely used by NDE experts around the world as an electronic bulletin board. Subscribers are added electronically and they receive via e-mail inquiries, data, information and announcements of general interest. Global efforts and initiatives of individuals and companies are contributing greatly to the field. As an example, the electronic publishing forum, *NDT.net*, is a highly active and effective web-system that combines an electronic journal, information archive and monthly technical forums of information exchange [http://www.ndt.net/newsweb/newsweb.htm]. To take advantage of the various web capabilities the author formed the JPL's NDEAA webhub [http://ndeaa.jpl.nasa.gov/] with clickable animation to aid understanding various mechanisms and with links to downloadable recent publications. Moreover, to quickly find and access the growing number of homepages of international technical societies, the author formed the Global NDT Internet Superhub (GNIS) with clickable countries on a globe map [http://eis.jpl.nasa.gov/ndeaa/nasa-nde/gnis/gnis.htm]. The technology reached a point where "companies do not exist unless they have a homepage". To find some of the major homepage addresses, one can use the NTIAC webpage that has links to over 300 NDE site [http://www.ntiac.com/]. Through its homepages, ASNT is offering society information such as various services, conferences, and other relevant activity and announcements [http://www.asnt.org/].

Inspection Simulation

Ray tracing is an essential tool for investigating the travel path of waves and developing test procedures. With the progress and increased speed of computer graphics it became feasible to investigate ray tracing using rapid interactive simulation. Simulation software can perform 3D ray tracing, and examine the wave interaction with the test structure geometry while accounting for the materials that are involved. Effective tools were developed by such research institutes as the Center for NDE at Iowa State University and the Canadian National Research Council as well as commercially by UTEX (Ontario, Canada). Computer models were used to develop user-friendly, accurate and rapid simulation of such methods as radiography, ultrasonics, and eddy current. Numerous test parameters were included in the models, e.g., for X-ray simulation (see example in Figure 1) some of the parameters are X-ray source, film type, part geometry, setup distances, exposure value, material absorption, etc. The part structure can be described using 3-D CAD models, and many types of defects can be inserted anywhere into the model to form a realistic simulation of the test process. In the case of modeling ultrasonics, the reflected, transmitted and refracted waves can be used to produce simulated A-, B-, and C-scans. Further, for eddy current the real and imaginary components of the impedance-plane output as a function of the probe position can be simulated in response to crack-like defects.



a. A honeycomb sandwich. **b**. A penetrameter gauge

Figure 1: Simulated radiographs using computer code and interactive graphics (Iowa State University).

Ultrasonic test procedures can be developed using complex real-world parts (see example in Figure 2); a complete ultrasonic inspection can be simulated including the test results; difficult problems can be anticipated and diagnosed by confirming the source of the returning echoes; the sound paths in the part can be visualized; the sound field of the transducer can be evaluated to make an effective choice of the transducer; and inspectors can be easily and effectively be trained. Specifically, A-scan displays for various angles of incidence can be simulated to assist inspectors in developing ultrasonic test procedures. Longitudinal and shear mode conversions can be identified by the operator and assist in explaining the origin of echoes that appear on an A-scan display. Moreover, simulated B-scans can display how stray sound modes and part geometry might accidentally shadow flaws. If fixturing is required, the simulation software provides the necessary information for the probe angulation, spacing, delay line or water-path distances. Transducer modeling features can simulate both contact and immersion coupling using various frequencies and bandwidths as well as various focal geometries (circular, elliptical or rectangular). Tests can be viewed in both pulse-echo and pitch-catch and the transducer can be manipulated to follow the part surface at a fixed distance and/or inspection angle. In Figure 3, an example of the application of simulation software is shown for the inspection of an IIW calibration standard as a means of determining the resolution of the test technique. The operator can use the simulation and the results of the actual calibration to verify the efficiency of the inspection procedure. The technology significantly simplified the development of test procedures and its application to process development is highly cost effective.

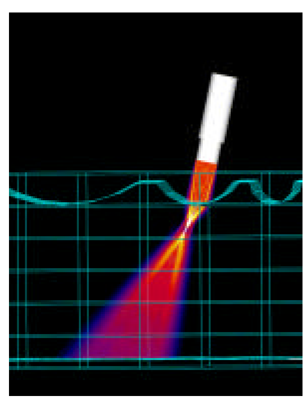


Figure 2: Simulation of the ultrasonic wave interaction with a complex configuration using ray tracing and computer graphics [Iowa State University, http://www.cnde.iastate.edu/staff/mgarton/mgarton.html].

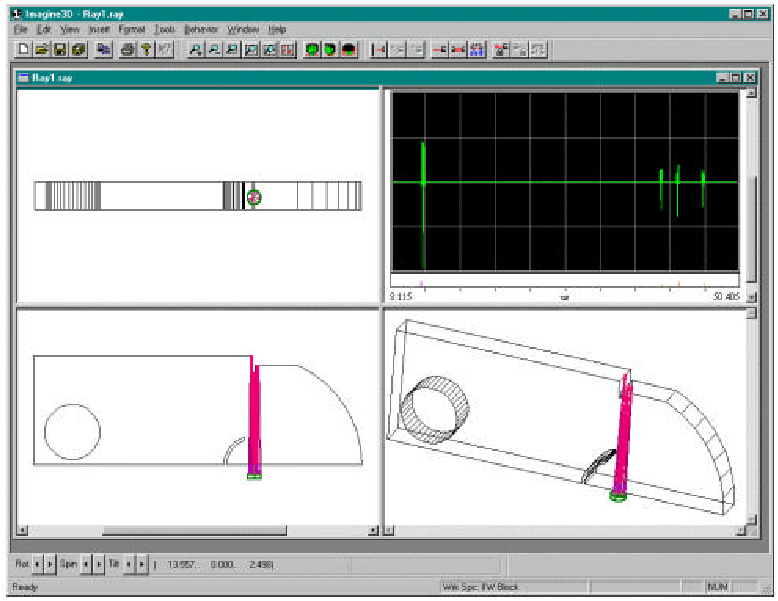


Figure 3: Inspection of an IIW block using simulation software (UTEX's Imagine3D)

Miniaturization

Progress in microelectronics enabled the miniaturization of NDE hardware and the production of portable instruments that can be carried to the field and reach difficult to access areas. Pocket size ultrasonic thickness gauges are commercially available from most of the leading manufacturers of ultrasonic instruments. The technology is leading to reduction in cost as well as in instrumentation weight and size with greatly enhanced capability. Data acquisition cards that can be plugged into a laptop computer have been available for several years (e.g., Wesdyne International, California) and credit card size plug-ins that conform to the PCMCIA type 2 standard is one of the forms in which this progress is expressed. The use of such cards allows converting laptops to small ultrasonic pulser/receiver and with appropriate software they can be operated as a complete ultrasonic data acquisition and imaging system. Plug-in cards are available for motion control (encoder) interfaces, high-resolution A/D converters and signal processors for potable scanners. Increasingly, systems that are battery operable are being used with wireless communication capabilities.

The technology of miniaturization has impacted also the size of sensors and their support electronics. For over ten years, the trucking industry has been using tires with imbedded sensors that wirelessly communicate every several minutes the individual tires' identity and pressure. Using effective power management, these sensors can operate for periods of more than 8 years without needing to change battery. This technology is intended to help truck drivers avoid tragic and costly accidents that can result from flat tires. Another area of automotive that benefited from miniaturized technology is impact sensing and the activation mechanism of airbags. Further, insects such as bees are commonly tracked with the aid of miniature transmitters that are installed as backpacks. Such capabilities can be transitioned to the field of acoustic emission and other NDE if miniature wireless stick-on sensors are used. The size of electronics has become so small that insects can be instrumented to perform tasks that used to be viewed as science fiction. Example is shown in Figure 4, where a spider at the University of Tokyo, Japan, was instrumented as a locomotive to carry a backpack of wireless electronics, and CCD imager. Development in actuation technology is expected to lead to insect-like robots that can be launched into hidden areas, such as aircraft engines, and perform inspection and maintenance tasks. Beside miniaturization of conventional actuators, such as motors, electroactive polymers (EAP) are being developed to offer the closest emulation of biological muscles. One of the applications that is currently being explored include a dust-wiper using the bending characteristics of ion-exchange type EAP materials operating similar to an automotive windshield wiper [Bar-Cohen, 2000a].

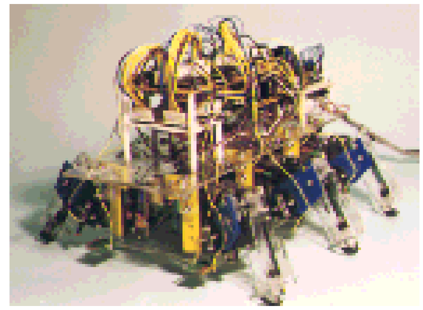


Figure 4: An instrumented spider at the University of Tokyo illustrates the potential to NDE in terms of mobile sensors [http://www.leopard.t.u-tokyo.ac.jp/].

Rapid field inspection

Performing NDE using such methods as ultrasonics and eddy current, which require a probe to obtain data and scanning to cover large areas, is time consuming and involves difficulties when applied in field conditions. Rapid inspection of large structures is an ongoing challenge to the NDE community. The need for such a capability grew significantly in recent years as a result of the increase in the numbers of aircraft with composite primary structures and the large number of aging aircraft still in service. Generally, metallic structures are susceptible to corrosion and fatigue cracking whereas composites are sensitive to impact damage that can appear anywhere on the structure. Using manual scanning, field inspection is labor intensive, time consuming and susceptible to human error, whereas removal of parts from an aircraft for a lab test is costly and may not be practical. Effective field inspection requires a portable, user friendly system that can rapidly scan large areas of complex structures. In recent years, various portable inspection systems have emerged including scanners that are placed at selected locations and sequentially repositioned to fully cover the desired areas [Bar-Cohen, 2000b]. An example of such scanner is shown in Figure 5, where vacuum suction cups are used to secure the attachment of the scanner-bridge to the test structure. The development of such scanners requires multidisciplinary expertise including NDE, telerobotics, neural networks, automated control, imbedded computing and materials science. The capability of the developed systems followed the technology evolution and the overall trend is towards full automation with a desire to have a completely autonomous inspection.

Increasingly, crawling devices are reported as a solution to the need for rapid inspection and the use of suction cups has become a leading form of controlled adherence. In contrast to aerospace use of suction cups, magnetic attachment techniques are used in pipelines, marine and other ferromagnetic structures. Several successful mobile portable scanners have emerged in the last several years, including the Automated Non Destructive Inspector (ANDI) and the Autocrawler [Bahr, 1992, and Siegel, 1998]. Recently, JPL developed the Multifunction Automated Crawling System (MACS) offering an open architecture robotic platform for NDE boards and sensors [Bar-Cohen & Backes, 1999]. MACS is a small, highly dexterous crawler designed to perform complex scanning tasks. It uses suction cups for controlled attachment and ultrasonic motors for mobility. MACS (shown in Figure 6) was designed for inspection of large structures particularly in field and depot conditions and it established the foundations of "walking" computer platforms using standard plug-in NDE boards. This concept offers larger pool of companies and individuals the opportunity to become producers of NDE modules without the need to fabricate instruments. Thus, a significant cost reduction can be materialized from such a focus, equivalent to manufacturers of modems and other computer components. It will be possible to novel concepts with rapid transition of to practical use. Such a trend can lead to rapidly improving, affordable and tailorable systems with potential success similar to the personal computers.

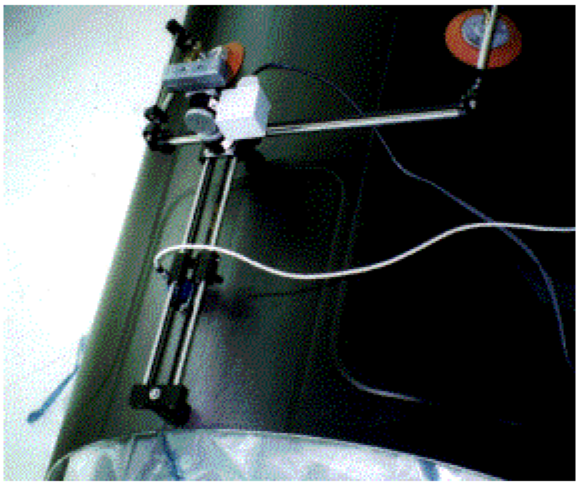


Figure 5: A scanner is secured to a test structure using suction cups (QMI, Costa Mesa, CA).

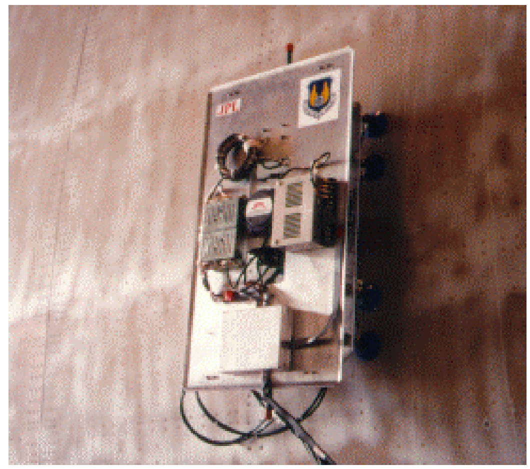


Figure 6: The JPL developed MACS crawling on the C-5 aircraft.

Remote monitoring is one of the avenues of future development where centrally located experts can be responsible for the inspection and they will be equipped with know-how, database, analytical tools, CAD drawing, and accept/reject criteria. These experts will need to deal only with questionable information where the redundant non-defective areas will be screened by the crawler system. Controlling the crawler remotely via Internet using password will allow authorized users to simultaneously view and control its operation. Inspection needs can be addressed rapidly, particularly in cases of crisis where it is necessary to examine a full flight of a particular aircraft model all over the world. A combination of visual, tap testing, eddy current, and ultrasonics are expected to be the leading NDE capabilities for integration into MACS. The evaluation of flaws using multiple NDE methods requires data fusion [Gros, 1996] and neural network data interpretation. Programming the travel on complex structures can employ telerobotic capabilities similar to the one developed for the exploration of Mars, including the rover of the Mars Pathfinder mission. MACS is currently using an umbilical cord for power, control, and communication as well as pressure tubing for ejection and activation of the vacuum suction cups. Further enhancement will be the development of an autonomous crawler for operation during aircraft idle time to reduce the need to ground aircraft for inspection. This will require miniature on-board vacuum pump, power and computing capabilities. To protect aircraft elements that rise above the surface from accidental damage, a vision system and collision avoidance software need to be used. Employing local Global Positioning Systems (GPS) can provide absolute coordinates without the need for complex, costly and heavy encoders. The information regarding the location of the crawler on the aircraft in relation to the detailed drawings can help assessing flaws criticality.

Testbed for Validation of New NDE Techniques

The need for a testbed to demonstrate new NDE techniques and instruments hampered the transition to practical use. In August 1991, an FAA center for NDE was formed at Albuquerque, NM, to offer a validation testbed consisting of aging aircraft with known flaws. This Sandia National Laboratories' Airworthiness Assurance Nondestructive Inspection Validation Center (AANC) was facilitated with a series of aging civilian aircraft and a library of structural parts with documented flaws [http://www.sandia.gov/aanc/pubs.htm, Smith & Shurtleff, 1997 and Shurtleff, et al, 1997]. The center arose out of the Aviation Safety Act of 1988, passed by Congress after the midair structural failure of the Aloha Airlines Boeing 737. Sandia's role has since been expanded to other areas covering aircraft overall safety system design such as fire protection, information system management, and accident investigation support. A view of one of the aircraft that is available at the AANC facility is shown in Figure 7.

Figure 7: An aging aircraft with well-documented flaws at AANC (Sandia National Labs).

NDE CONCERNS AND CHALLENGES

The continuing need for improved NDE methods resulted from the fact that any of the known methods has certain capabilities and limitations in detecting flaws and/or determining material properties. The selected method(s) and inspection requirements depend on the inspected material structure and the life cycle stage. While in-service inspection of metallic structures requires mostly the detection of fatigue cracks and corrosion, composite structures require the detection of delaminations and impact damage. Generally, unless a crack is located in a stack of plates beyond the second layer, many methods are available for its detection. Cracks need to be detected above a critical size and their size and depth need to be determined. In contrast to this relatively simple requirement, corrosion detection and characterization and NDE of composite structures are more complex.

Metallic Structures in Service

In service, two major types of flaws are commonly sought: fatigue cracks and corrosion. Generally, fatigue cracks are initiated at high cyclic stress areas and therefore it is relatively easy to determine when and where to expect them and their geometry is relatively simple. On the other hand, the issue of corrosion damage is much more complicate and it can consist of complex geometry and variety of types (see Table 1). The damage is a relatively slow material degradation process [Hagemaier, Wendelbo & Bar-Cohen, 1985]. Corrosion is a general term that describes the oxidative degradation of metals caused by a local galvanic cell between the base metal (acting as anodic sites), at sites of defective protective coating, having the passive sites sustaining cathodic reaction. The corrosion process converts the metal into its oxide or hydroxide forms resulting in deterioration of its mechanical properties. Corrosion in aluminum alloys and plated steel surfaces can often be recognized by dulling or pitting of the area, and sometimes by white or red powdery deposits. It may also be the origin of, or revealed by, delamination, cracking, metal thinning, fretting, etc. Corrosion can appear in many forms, depending on the type of metal, how it is processed, its surrounding structure and service conditions. Corrosion results from exposure to humid or corrosive environments and involves primarily electrochemical action at chemical/metallurgical/physical heterogeneity with dissimilar potentials. Table 1 lists the various corrosion types that may appear in aircraft metallic components, their sources of formation and by-products.

Aircraft are designed and manufactured with built-in corrosion-prevention features. However, most metals used in aircraft structures are subjected to degradation due to exposure to adverse environments including humidity-induced stresses and wide temperature excursions. These conditions may cause localized corrosion attacks in various forms. Corrosion-protection systems are widely in use and they consist of a combination of materials, sealants, paints, design details, drainage, assembly practice, and preventive maintenance. The corrosion-prevention system cannot be guaranteed to work. The severity of corrosion attacks varies with aircraft type, design techniques, operating environments, and operators' maintenance programs.

In spite of careful maintenance programs to assure a lower rate of progress of corrosion damage (proper sealing or cleaning in galley area, proper draining, etc.), corrosion does occur and effective NDE techniques are needed to detect them as early as possible. Detection of each of the corrosion types described in Table 1 may require a different NDE approach due to the unique characteristics that are involved. Recent efforts are directed to avoiding removal of the paint or coating prior to inspection in order to minimize the associated environmental impact as well as cost. Several NDE methods are widely used for corrosion detection and evaluation. When the inspected area is physically accessible, visual tests are commonly used for periodic checks in search for cracks, change of color, change of texture, or bulges. Sometimes, tools such as magnifying glasses or boroscopes are employed for further evaluation or for less accessible areas, respectively. Surface corrosion at its embryonic stage can be visually detected from localized indication such as discoloration, faint powder lines, pimples on the paint and paint damage. Concealed corrosion is very difficult to detect since in most cases the characteristics of the damage are not sufficient to trigger an indication in conventional NDE tests. Generally, several NDE methods are available to detect and characterize hidden corrosion including X-ray and neutron radiography, ultrasonics, eddy current, and acoustic emission. All existing NDE methods for detection of corrosion are limited in capability and sensitivity. Frequently, corrosion is detected only after several subsequent inspection schedules, in which case the damage is fairly extensive and may require the replacement of the structural component involved.

TABLE 1: Corrosion types, which can inflict damage to aircraft strictures, and their characteristics.

Corrosion type	Source	Appearance	By-Product	Notes
Crevice	Afflicts mechanical joints, e.g., coupled pipes or threaded connections. Triggered by local environment composition differences (O_2 concentration).	Localized damage in the form of scale and pitting.	Same as scale and pitting.	• Caused by differential aeration. • Difference in oxygen concentration produces potential difference and leads to flow of electrical currents across aerated (cathode) and derated (anode) portions of the metal. • Causes localized corrosion failure.
Filiform	High humidity around fasteners, skin joints or breaks in coating cause an electrolytic process.	Meandering, fine, thread-like trenches spreading from the source.	Similar to scale.	
Galvanic Corrosion	Corrosive condition that results from contact of different metals.	Uniform damage, scale, surface fogging or tarnishing.	Emission of mostly molecular hydrogen gas in a diffused form.	• Slow growth rate. Expressed as penetration/year or weight loss per unit-area/day, e.g. the rate for aluminum in open atmospheric conditions of Los Angeles, CA is 0.02-mil/yr. • For Ti and Al alloys the rate is slow and therefore it does not pose serious structural problems. • The metal with the most negative potential suffers the most damage.
Inter-granular	Presence of strong potential differences in grain or phase boundaries.	Appears at the grain or phases boundaries as uniform damage.	Produces scale type indications at smaller magnitude than stress corrosion.	• The severity and rate of growth depends on the material microstructure crystalinity and segregation. • This type of corrosion can merely result increased susceptibility to attack in the form of pitting or stress cracking. • Exfoliation occurs in layered grains (e.g. rolled sheets) in the form of laterally extended damage. • Aluminum is susceptible to such attack mainly in an environment of chlorine ions and dissolved oxygen.
Microbial	Bacterial, fungus or yeast in contaminated kerosene-type jet engine fuel.	Appears in integral fuel tanks.	Combination of by-product of pitting and scale.	Can be eliminated by a proper maintenance of the fuel in the tank.
Pitting	Impurity or chemical discontinuity in the paint or protective coating.	Localized pits or holes with cylindrical shape and hemispherical bottom.	Rapid dissolution of the base metal.	• Expressed in terms of pitting depth (i.e. pitting factor). • Pitting can be critical to the structural integrity. • Can be detected by AC impedance or electrochemical impedance spectra analysis.

				• Usually pitting is accompanied by an order of magnitude change in the local resistance and capacitance.
Stress Corrosion Cracking	Mechanical tensile stresses combined with chemical susceptibility.	Localized micro- macro-cracks at shielded or concealed areas.	Produces initially scale type indications at a large magnitude that progresses to cracking.	• Causes critical failure of structures. • Failure rate is determined by the stress levels. • Corrosion fatigue occurs under cyclic stresses. • Stress and rubbing action remove protection and lead to fretting corrosion as a result of contact of the metal surface with particles introduced by the abrasion process.
Thermo-galvanic Corrosion	Caused by thermal gradients parallel to the metal surface.	Localized attack correlated with temperature distribution.	Produces scale indications.	Hot portion of the metal serves as cathode whereas the cold portion as anode.

NDE of Composite Materials

The high stiffness to weight ratio, low electromagnetic reflectance and the ability to embed sensors and actuators have made fiber-reinforced composites an attractive construction material for primary aircraft structures. These materials consist of fibers and a polymer matrix that are stacked in layers and then cured. A limiting factor in widespread use of composites is their high cost - composite parts are about at least an order of magnitude more expensive than metallic parts. The cost of inspection is about 30% of the total cost of acquiring and operating composite structures. This large portion of the total cost makes the need for effective inspection critical not only to operational safety but also to the cost benefit of these materials [Bar-Cohen, et al, 1991]. Currently, there are several critical issues that are still challenging the NDE community with regards to inspection of composites. These issues include:

- **Defect Detection and Characterization**: Throughout their life cycle, composites are susceptible to the formation of many possible defects mostly due to the multiple step production process and their non-homogeneity with brittle matrix. These defects include delaminations, cracking, fiber fracture, fiber pullout, matrix cracking, inclusions, voids, and impact-damage. Table 2 lists some of the defects that may appear in composite laminates and their effect on structural performance. While the emphasis of most practical NDE is on detection of delaminations, porosity and impact damage, Table 2 shows that other defects can also have critical effect on host structures. Therefore, it is essential to be able to characterize the flaws in order to determine their degradation effect on the structural integrity.
- **Material Properties Characterization**: Production and service conditions can cause degradation of properties and sub-standard performance of primary structures. Sources for such degradation can be the use of wrong constituent (fiber or matrix), excessive content of one of the constituent (resin rich or starved), wrong stacking order, high porosity content, micro-cracking, poor fiber/resin interface aging, fire damage, and excessive environmental/ chemical/radiation exposure. Destructive test methods of determining the elastic properties are using representative coupons. These methods are costly and they are not providing direct information about properties of the represented structures.

TABLE 2: Effect of defects in composite materials

Defect	Effect on the material performance
Delamination	Catastrophic failure due to loss of interlaminar shear carrying capability. Typical acceptance criteria require the detection of delaminations that are $\geq$0.25-inch.
Impact damage	The effect on the compression static strength • Easily visible damage can cause 80% loss • Barely visible damage can cause 65% loss
Ply gap	Degradation depends on stacking order and location. For $[0,45,90,-45]_{2S}$ laminate: - 9% strength reduction due to gap(s) in 0^{o} ply - 17% reduction due to gap(s) in 90^{o} ply
Ply waviness	• Strength loss can be predicted by assuming loss of load-carrying capability. • For 0^{o} ply waviness in $[0,45,90,-45]_{2S}$ laminate, static strength reduction is: - 10% for slight waviness - 25% for extreme waviness • Fatigue life is reduced at least by a factor of 10
Porosity	• Degrades matrix dominated properties • 1% porosity reduces strength by 5% and fatigue life by 50% • Increases equilibrium moisture level • Aggravates thermal-spike phenomena
Surface notches	• Static strength reduction of up to 50% • Local delamination at notch • Strength reduction is small for notch sizes that are expected in service
Thermal Over-exposure	Matrix cracking, delamination, fiber debonding and permanent reduction in glass transition temperature

- **Rapid Large Area Inspection**: Impact damage can have critical effect on the capability of composite structures to operate in service. This critical flaw type can be induced during service life anywhere on the structure and it requires detection as soon as possible rather than waiting for the next scheduled maintenance phase. Using conventional NDE for the assurance of the structural integrity can be very expensive and takes aircraft out of their main mission. Since impact damage can appear anytime and anywhere on the structure, there is a need for a low-cost system that can be used to rapidly inspect large areas in field condition. The use of a robotic crawlers can potentially offer effective platform for rapid inspection of composite structures.
- **Real-Time Health Monitoring**: Structurally integrated health monitoring systems are needed to reduce the need for periodic inspection and temporary removal of aircraft from service. Fundamentally, such health monitoring systems emulate biological systems where onboard sensors track the structural integrity throughout the life cycle. Such systems can monitor changes in the characteristics of critical parameters and activate an alarm when certain values are exceeded.
- **Smart Structures**: The availability of compact actuators, sensors and neural networks has made it possible to develop structures that self-monitor their own integrity and use actuators to avoid

or timely respond to threats. The changing environment or conditions can be counteracted by adequate combination of actuators and sensors that change the conditions and/or dampen the threat. Sensor fusion, neural network and other artificial intelligence capabilities can be used to assure making the most effective and quick response. An example of the application of smart structures is the reduction of vibrations that lead to fatigue.

- **Residual Stresses**: Current state of the art does not provide effective means of nondestructive determination of residual stresses. Technology is needed to detect and relieve residual stresses in structures made of composite materials.
- **Weathering and Corrosion Damage**: Composites that are bonded to metals are sensitive to exposure to service fluids, hygrothermal condition at elevated temperatures and to corrosion. Particular concern rises when aluminum or steel alloys are in a direct contact with composites that consist of graphite fibers or carbon matrix. Graphite is cathodic to aluminum and steel and therefore the metal, which is either fastened or bonded to it, is eroded. In the case of graphite/epoxy the metal deteriorates, whereas in the case of graphite/polyimide defects are induced in the composite with the form of microcracking, resin removal, fiber/matrix interface decoupling and blister (e.g. delaminations).

For many years, the multi-layer and the anisotropic nature of composites posed a challenge to the NDE research community. Pulse-echo and through-transmission are still the leading standard NDE methods of determining the quality of composites. However, these methods provide limited and mostly qualitative information about defects and material properties. The discovery of the Polar Backscattering and the leaky Lamb wave (LLW) phenomena in composites enabled effective quantitative NDE of composites [Bar-Cohen, et al, 1991].

CONCLUSIONS

The beginning of the third Millennium provides a milestone point to look back at the progress that was made in the field of NDE and take a snapshot of its state-of-the-art as well as determine the challenges that are still constraining the technology. Like many other fields, improvements were made in every aspect of the NDE science and engineering where computers and internet contributed greatly to the rapid advancement. Efforts are increasingly being made to integrate several methods to form multi-mode systems that take advantage of the complementary capabilities to increase the functionality and the overlapping capabilities to improve the reliability.

Some technologies affected most or all the NDE methods and those include internet, interactive inspection simulation, miniaturization, portable robotics, and others. Inversion techniques were developed to extract flaw characteristics and material properties using nondestructive measurements. In addition to developing improved methods, various sensors are now available to perform a wide range of inspection tasks. The available sensors can be grouped as follows:

- Remote sensors - Eddy current, magnetic, visual, dry-couple ultrasonics, etc.
- Attached sensors - Cracking fuse, resistance gauging, strain gage, acoustic emission, ultrasonic, eddy current, fiber optics
- Sensitive coating - Bruising paint indicator, brittle coating, liquid crystals
- Imbedded sensors - Fiber optics, dielectric, eddy current, magnetic, ultrasonics

The most practical sensors currently used are the ones that either can be operated remotely or attached to the test structures. The manufacturers and users are still not receptive to using sensors that can be imbedded, permanently attached or coated. This is due to the weight increase and the potential effect on the structural integrity. The use of stick-on wireless type sensors is expected to emerge in the coming years to allow monitor structural integrity throughout the life cycle of structures without disassembly, redesign or complex wiring.

The use of the crawler technology is offering great potential to rapid field inspection, where plug-and-ply boards would define the crawler functionality. Employing off-the-shelf components and standard personal computers bus structure (e.g., ISA, PCI etc.) can lead to significant reduction in system cost. Currently, NDE hardware manufacturers have to develop a complete instrument each time new product is introduced. It is envisioned that concentration on the development of components with focused NDE functionality (e.g., ultrasonics) will have great payoff. It would lead to substantially greater affordability of future instruments and to a faster transition of NDE technology to commercial use. Since the 96 ASNT Fall Conference, the author started holding Sessions on the topic of Robotics and Miniature NDE Instruments. The intent of these Sessions is to attract industry and academia attention to the topic of developing generic crawler similar to a PC motherboard as well as related plug-in modules. Recent government interest in addressing the issue of NDE of corrosion turned the spotlight onto the JPL's MACS crawler as a potential baseline for robotic multi-sensor platform for rapid scanning of aircraft structures. In future generations of this technology, micro-electronic mechanical systems (MEMS) is expected to lead to extremely small NDE instruments and scanners. Insect-size micro-scanners may potentially crawl into aircraft engines and other hidden areas and perform inspection or other maintenance tasks.

Inspection of hidden structures, composite materials and corrosion are still posing challenges to the NDE community. In the coming years, advancement in miniature electronics, actuators, robotics, wireless communication as well as sensors are expected to make great impact on the field of NDE. The search for smarter methods that can rapidly and inexpensively detect very small flaws in complex materials and structures at very high probability and repeatability will continue to be a challenge for NDE. Efforts will be made to further reduce the complexity associated with inspection procedures, where redundant tasks will be performed by computers leaving the role of the human operator to critical decision making tasks.

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